

## Investigation of voltage transformers operating modes in networks with insulated neutral terminal at non-symmetric modes

Artem Popov and Yuriy Sayenko  
Pryazovskyi State Technical University, Mariupol City, Ukraine

Bernhard Arndt  
University of Applied Sciences Würzburg-Schweinfurt

Ferroresonance and processes at one-phase grounding inside networks with insulated neutral terminal are investigated. It is shown that the mode with unidirectional arc, at which direct current passed in high voltage windings is the most difficult operating mode for the transformer. The influence of the secondary voltage transformer load upon the stability of ferroresonance oscillations has been also investigated.

Categories and Subject: Electricity and Electrical Engineering

Additional Key Words and Phrases: Ferroresonance, Magnetization Curve, One-phase Arc Grounding, Voltage Transformer, Zero-sequence Capacity

### 1 INTRODUCTION

Long-term exploitation of power networks with insulated neutral termination proved that the weakest point of such networks is the voltage transformer for insulation control. The data show that in the Ukraine 7-10% of all installed voltage transformers (VT) [1] get damaged every year. So, investigation of operating modes of VT seems to be of vital importance, as well as development of measures, aimed at raising their reliability.

Damage of VT is often accompanied with non-symmetric mode, particularly with one-phase arc grounding or ferroresonance. It results from substantial current flow in VT high-voltage winding, causing its overheating and thermal destruction. Both cases are to be discussed below.

### 2 MODELLING AND ANALYTICAL APPROACHES TO TRANSIENTS STUDIES

The method of imitational simulation, realized in MATLAB program was applied in this article for investigation of no-symmetric modes. The simplified equivalent circuit of the network under investigation is represented in Fig. 1, VT equivalent circuit, applied for simulation is

Author's address:

Yuriy Sayenko<sup>1</sup>, Artem Popov<sup>1</sup>, Bernhard Arndt<sup>2</sup>.

<sup>1</sup>Pryazovskyi State Technical University, 87500 Universytets'ka 7 str, Mariupol City, Ukraine

<sup>2</sup>University of Applied Sciences Würzburg-Schweinfurt

Email: yls@mail.ru, artempopov9@gmail.com, bernhard.arndt@fhws.de

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represented in Fig. 2, while Fig. 3 represents magnetization characteristics of VT of NTMI-6 type. Hysterisis-free VT model was used in our investigation.

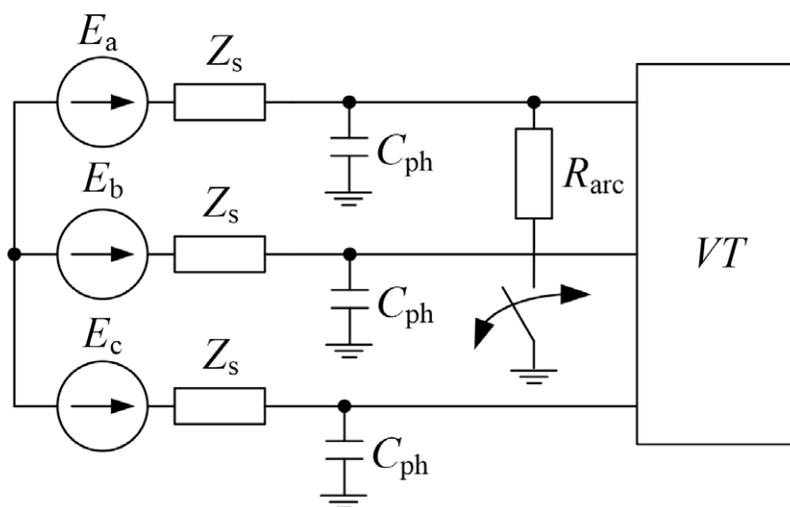


Fig. 1. Analytical model of substitution of the arc under investigation

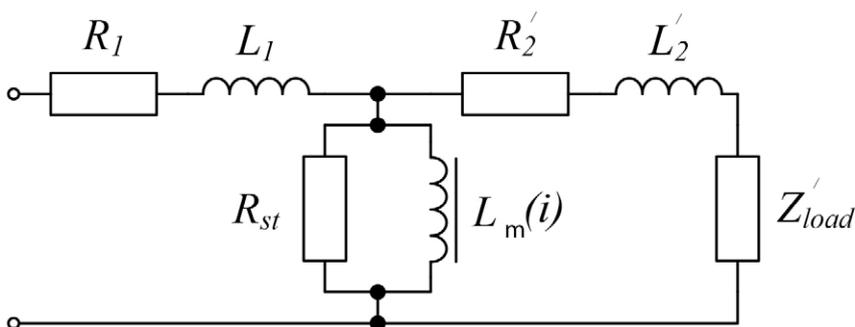


Fig. 2. The model of VT substitution

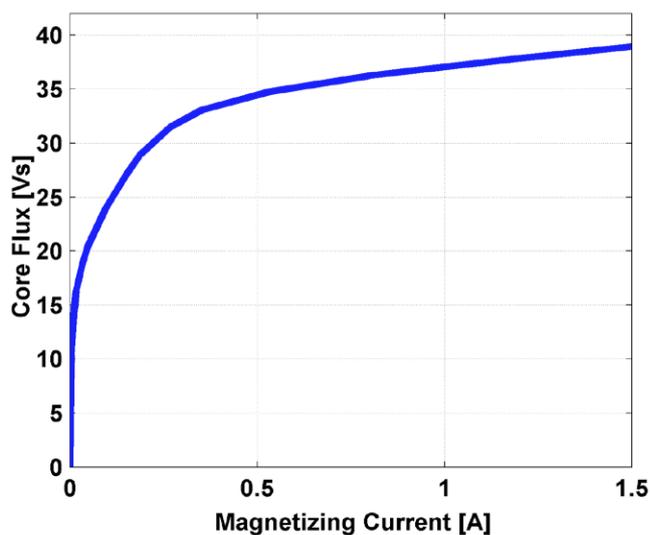


Fig. 3. Experimental the magnetization curve VT characteristics

The mode of one-phase metal shorting is not dangerous for VT. The voltage of not damaged phases is increased up to the value of linear voltage, the currents inside windings are but slightly raised, not exceeding the tolerable values. Much more serious consequences for VT happen to be in case of unstable shorting, i.e. at alternating arc. In this case overvoltages occur, the value of which could reach 2.6-3.2 p.u. [2], accompanied with VT core's saturation and the current inside high-voltage windings increases. Prolonged existence of this mode leads to thermal damage of high voltage winding. In Fig. 4 the curves, obtained by modelling of phase voltages and currents in the VT high voltage winding at one-phase arc shorting are summarized. The arc behavior is based on Petersen's theory, according to which the arc is started at the moment of the highest voltage in the damaged phase and is subsided at the moment the high-frequency component passes through zero. The current inside high voltage winding exceeds very much the long-term permissible value (0.3 A) and it inevitably leads to the damage of VT.

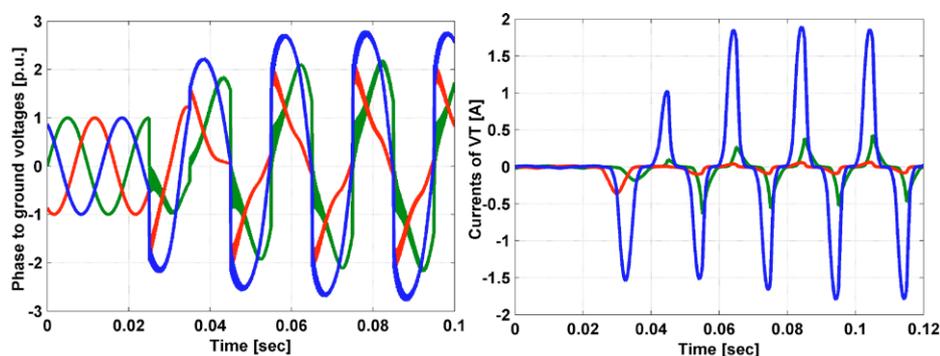


Fig. 4. Designed curves of phase voltages and currents in high-voltage VT windings at symmetrical arc shorting

Obviously, the value of currents in the winding becomes higher when repetition factor of overvoltages is raised. In the example discussed, the biggest value of repetition factor of overvoltages reached 3 p.u., this value very much exceeding the values, obtained by registering transitional processes in actual power networks. The main error at simulation is caused by overvoltage of arc-through, as at realization of Petersen's theory actual physical processes in insulation are not taken into account, that is why arc-through voltage could reach  $1.5 U_{pb}$  or higher, whilst the actual value of arc-through voltage fluctuates within  $0.6-1.0 U_{pb}$  range. The results of modeling showed that that if overvoltage reached 2.6 p.u. VT could operate for quite a long time without any thermal damage of high voltage winding.

The cases described above apply to symmetrical arc only, i.e. when the arc is struck at uniform voltage on positive and negative half-wave. Actual process of the arc flare can be non-symmetrical, resulting to different values of arc-through voltage on positive and negative half-waves. Unidirectional arc, which is ignited and subsides once throughout the period, is the ultimate example of non-symmetrical arc. Fig. 5 summarizes the appropriate designed curves of phase currents and voltages in high-voltage winding. Here, the currents are approximately equal and possess unidirectional character. It follows from oscillation diagrams of phase voltages that the area of positive and negative voltage half-waves differs. Hence, a constant component must be present in phase voltages.

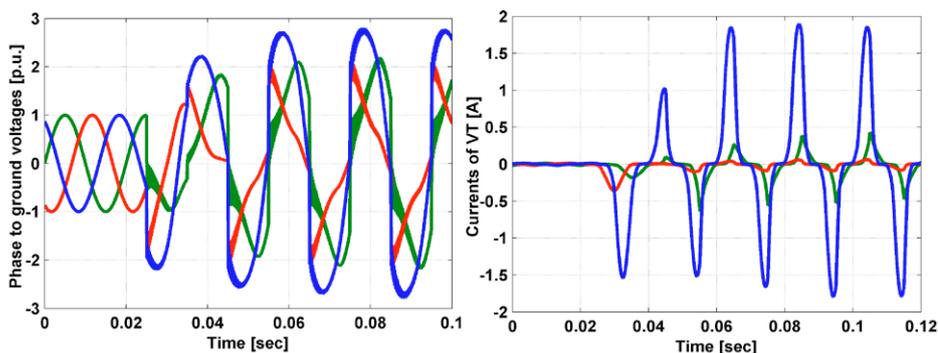


Fig. 5. Designed curves of phase voltages and currents in high-voltage VT windings at unidirectional arc

Fig. 6. summarizes amplitude-phase spectrum of B-phase voltage, from which it follows that the value of the constant component is equal to 650 V. That is why in this case magnetization of VT core with direct current happens, determined by the value of constant voltage and active resistance of high voltage winding, which for this VT is equal to 1200 Ohms.

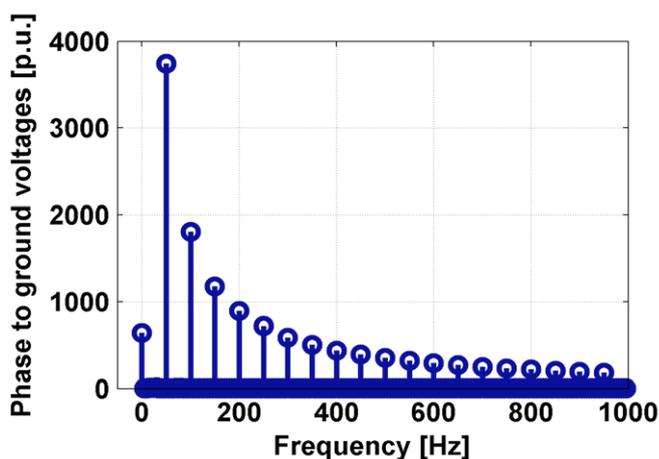


Fig. 6. Amplitude-spectrum of phase voltage at unidirectional arc

The mode of bidirectional non-symmetrical arc is less difficult but also dangerous. In this situation a constant component is also present in spectrum of phase voltages and VT is magnetized with direct current. However, the value of this constant component is smaller than in case of unidirectional arc. Investigations revealed that value of the constant component is determined by the relation of arc-through voltage on the positive ( $U_+$ ) and negative ( $U_-$ ) half-waves. The obtained dependence of the constant component  $U_{const}$  upon the relation of  $U_+/U_-$  is shown in Fig. 7. It should be noted here that experience of making oscillation diagrams, gained by the authors for many a year [2]-[4] showed that appearance of a non-symmetrical arc is an event, which is likely to happen, especially during the initial shorting stage.

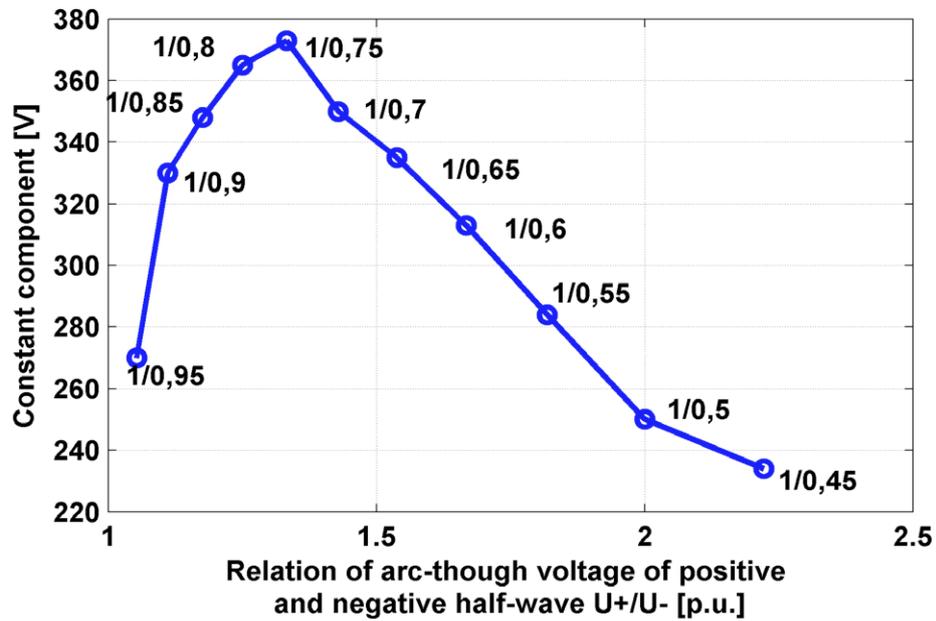


Fig. 7. The dependence of the DC component on the ratio of the breakdown voltage of the positive and negative half-wave

Ferroresonance mode is also dangerous for VT [5]-[7]. The biggest danger for VT is subharmonic ferro-resonance, which often occurs after one-phase shorting disappears. Low frequency component appears in phase voltages spectrum at subharmonic ferroresonance, which over-saturates VT rod, resulting in substantial currents passing through high voltage winding, leading to its thermal damage. An example of subharmonic ferroresonance is given in Fig. 8, where curves of phase voltages and currents in high voltage winding are shown. Phase grounding capacity ( $C_{ph}$ ) is equal to 0.6  $\mu$ F.

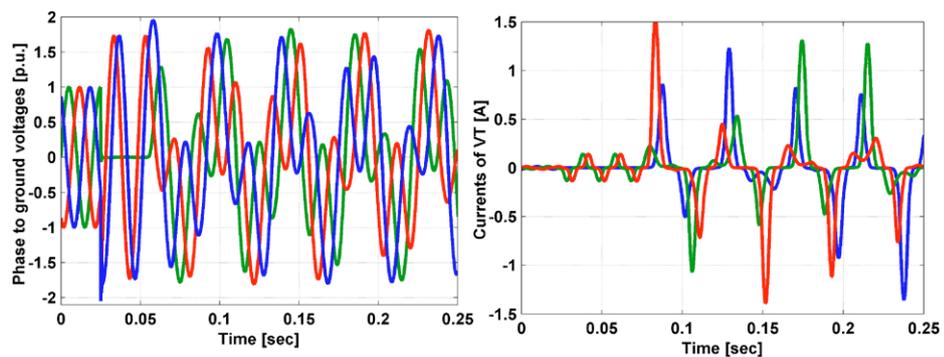


Fig. 8. Designed curves of phase voltages and currents in VT primary winding at subharmonic ferroresonance, which sprang up when grounding shorting was eliminated

Ferroresonance processes, developing at frequencies 50 Hz, or higher do not lead, as a rule, to thermal damage of VT. An example of ferroresonance, which originated when unloaded buses on VT were switched on, is given in Fig. 9, where phase voltages and currents in high VT voltage winding are shown. In comparison to subharmonic ferroresonance, ferroresonance processes at 50 Hz frequencies or higher are accompanied with bigger overvoltages, which could be dangerous of network insulation.

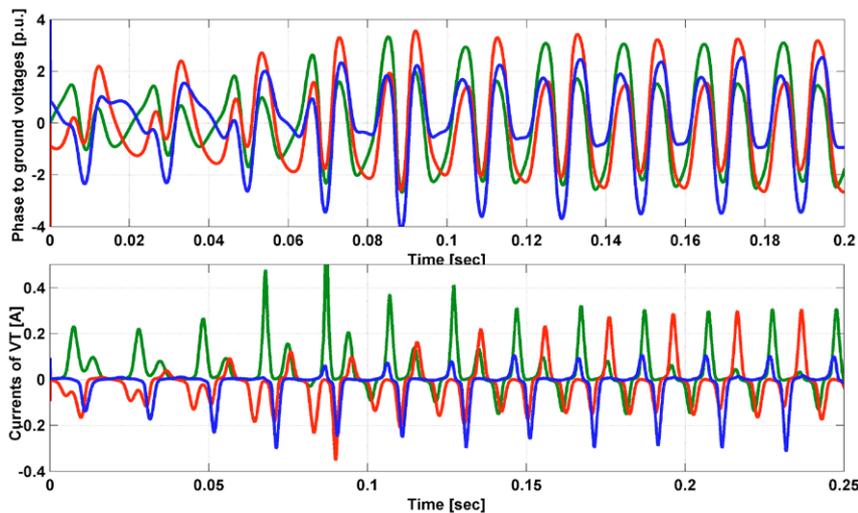


Fig. 9. Designed curves of phase voltages and currents in VT primary winding at ferroresonance, which sprang up when unloaded buses were switched on.  $C_{pb} = 0.012 \mu\text{F}$

When ferroresonance processes were modeled, the influence of the load of secondary VT winding upon the character of ferroresonance processes was investigated. The overall load of the secondary winding changed within 0-150 VA range at  $\cos \varphi = 0.8$  i.e. within the range, where VT operates in class 1 of precision. The results of investigation showed that increase of the load of the secondary winding diminished the probability of ferroresonance appearance, this being true for all types of ferroresonance. As an example, designed currents curves in the primary winding in case with unloaded VT are depicted in Fig. 10 (see Fig. 10 a) as well as in case with the load 150 VA (see Fig. 10 b). Phase grounding capacity is equal to  $0.6 \mu\text{F}$ .

It could be seen from curves, that, in case of loaded VT, ferroresonance fades away, i.e. the load damps ferroresonance. The damping efficiency gets higher alongside with the raise of the load in the secondary circuit. The obtained data are in conformity with the data obtained by exploitation [5], according to which the damaging rate of VT is inversely proportional to the load of the secondary winding. The Table 1 summarizes the dependence of failure flow of VT upon the load of the secondary winding.

Load of the secondary winding VT, VA	Up to 25	25 – 50	50 – 75	75 – 100	Over 100
Parameter of failure flow , 1/year	0.208	0.1383	0.1097	0.114	0.0513

Table 1: Dependence of VT failure rate upon the load of the secondary winding

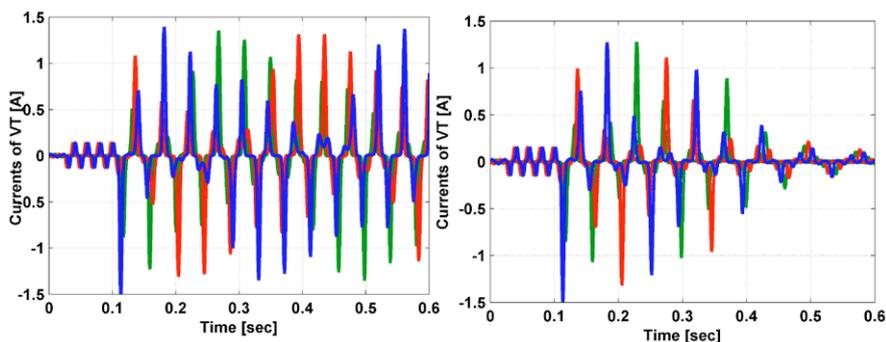


Fig. 10. Designed curves of currents in the high-voltage winding at unloaded VT (a) and when the load is 100 VA (b)

The calculations of ferroresonance, with unloaded buses on VT switched on, have also been made, VT's secondary load being 75 VA, phase grounding capacity being 0.015  $\mu\text{F}$ . The designed curves of phase voltages are summarized in Fig 11. Comparing them to the results, shown in Fig. 9 we may conclude, that amplitude of overvoltages has grown considerably smaller and the process of ferroresonance is fading.

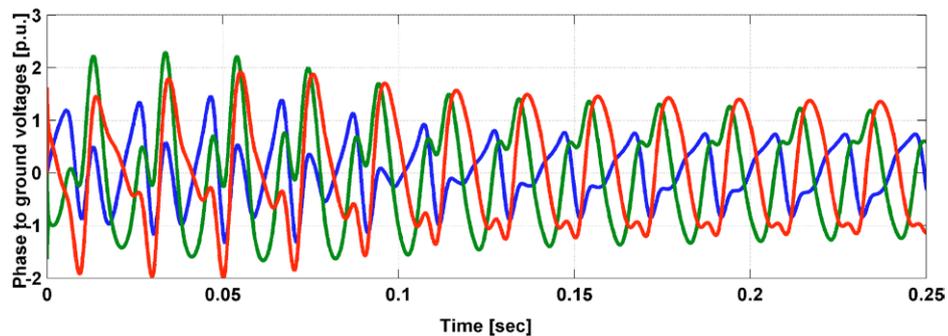


Fig. 11. Designed curves of phase to ground voltages, when VT with load on the secondary winding equal to 75VA upon no-load buses was switched on.  
 $C_{pb}=0.012 \mu\text{F}$

### 3 CONCLUSION

1. Damaging of VT can be caused by prolonged existence of arc shortings. The most difficult case is the mode of unidirectional arc, where rod becomes magnetized by direct current. In order to prevent VT damaging, measures should be specified for limitation of arc overvoltages, or limitation of time of intermittent arc existence.
2. The probability of ferroresonance appearance is inversely proportional to the load of VT secondary winding. So, we recommend to increase the load of the secondary winding up to maximal permissible value, according to the specified precision class, in order to diminish the risk of ferroresonance appearance.

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